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RAPID AND VERY RAPID EVOLUTION OF BUSHING FLAWS DETECTED BY ONLINE MONITORING

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ABSTRACT

Because many transformer flaws originate at the bushings, in order to reduce the shutdowns for tests the offline tests on bushings have been replaced by online monitoring, which has been providing new data on the defect form and time of evolution. In general, it was believed that the flaws in bushings evolve slowly, in weeks or months. While this is true in many cases, this paper presents the experiences by Brazilian electric power utilities Chesf and Eletrosul, in which online monitoring data indicated flaw evolution times of minutes or hours. A new methodology for fault detection and rapid evolution alarm will be introduced which, when used with the current slow evolution flaw detection techniques, will result in an increased reliability of the electric power supply.

KEYWORDS

Online monitoring, Bushings, Flaws, Diagnosis, Prognosis.

1.0 - INTRODUCTION

According to CIGRE 1983 statistics, obtained from a transformer failure international survey [1], a large portion of the flaws starts at the condensive bushings: 33.3% in no-OLTC plant transformers, 20% in no-OLTC substation transformers and 12.3% in OLTC substation transformers, as shown in Figure 1. Despite the lack of recent statistics on the subject, the history of events [2] involving bushings in the last two years in Brazil in recent years seems to confirm the important role of these flaws in the overall transformer flaw incidence.

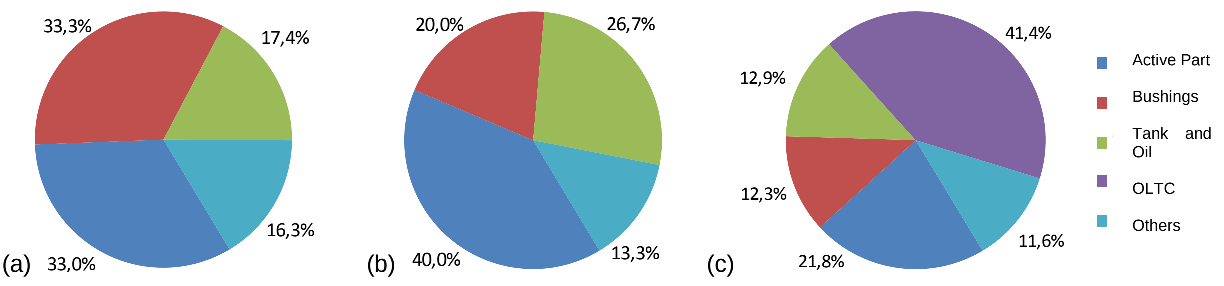

Fig. 1. Statistics of transformer downtime causes. (A) No-OLTC plant transformers; (b) no-OLTC substation transformers (c) OLTC substation transformers [1].

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As a result, several online monitoring systems have been applied by the electric utilities in Brazil and worldwide, with a strong trend to replace the offline tests by online monitoring, mainly at the generating and transmission plants, but with applications also at the distributing plants.

These systems, while reducing the likelihood of catastrophic events through early detection of defects, lowering the operating and maintenance costs and reducing or eliminating downtime to test bushings, also have fulfilled the important role of providing new data on the way defects evolve in bushings, something rarely available so far, since in most cases the existence of the defect only becomes known after the failure, when a great part of the information has already been destroyed.

Common sense and experience in the electricity sector with the operation and preventive maintenance of transformers and power reactors tend to indicate that, in general, the evolution of defects in bushings is slow, taking weeks or months. This is a premise that has been used broadly in the market for the operation of online bushing monitoring systems, which is based on it. In fact, this assumption may be true in many cases, as confirmed by experiments with offline measurements on bushings and, more recently, with online monitoring, which detected the evolution of a defect and prevented bushing failure with a scheduled stoppage for replacement [2].

However, data not previously available which are now available thanks to the online monitoring systems show that this is not always true. This paper presents the experiences by Chesf and Eletrosul with bushing online monitoring and data evolution of defects in the bushings, indicating that the evolution times can be much shorter than expected. The form and speed of evolution of the flaws shall be compared with experiences in which the evolution was slow.

2.0 - CONDENSIVE BUSHING ONLINE MONITORING

Capacitance and Tangent Delta measurements of the bushing insulation are well accepted indications to diagnose the status of this equipment. ANSI / IEEE C57.19.100-1995 standard [3], published prior to the popularization of online monitoring, suggests typical ranges from 3 to 6 years to conduct these measurements offline. A comparative study [4] between the offline measurements of these parameters and analysis of gases dissolved in bushing oil with suspected defects in evolution testifies to the effectiveness of the capacitance and tangent delta measurements for the diagnosis of bushing defects.

However, the offline and periodic measurement of these parameters largely negates its effectiveness because of the possibility of defects developing in the interval between two measurements, probably resulting in serious failure; of the need to shut down the equipment to carry out the measurements with its consequent downtime and costs, which reduces the overall reliability of the electrical system; and of using maintenance teams, which are usually small, perform the tests.

Thus, capacitance and tangent delta online monitoring of condensive bushings has established itself as the answer to these drawbacks, to continuously monitor possible changes in these parameters, allowing the detection of defects in the insulation at an early stage.

Several techniques have been employed in bushing online monitoring. Among them, the bushing current leakage vector sum in a three phase assembly has stood out due to the following characteristics:

- It allows online monitoring of changes in both the capacitance and the Tangent Delta - some other techniques are not able to monitor the Tangent Delta;

2.1 <u>It does not require the measurement of phase-ground voltages applied to the bushings, which is needed in some of the other measurement techniques - often there are no power transformers available at the facility to provide this voltage information.</u>

In each of the bushings the leakage current flows through C1 capacitance to ground through the capacitive tap, and this current is a function of phase-ground voltage and the insulation impedance. Therefore, any alteration in the insulation impedance (capacitance or tangent delta) will reflect in a corresponding alteration in the leakage current that, theoretically, could be used to detect the change in impedance.

However, one of the obstacles to detection, as described above, is the magnitude of the changes that the client desires to monitor. Changes as small as an algebraic increase of 0.3% in the tangent delta of a bushing may represent the difference between a new bushing in good repair and a bushing at the acceptable threshold. It is evident that such a small change in the dissipation factor will cause an almost negligible change in the leakage current of the bushing, making it unfeasible to detect it only by monitoring each bushing's leakage current.

In order to overcome this difficulty, the technique of the vector sum of the leakage currents takes advantage of the fact that the three leakage currents are out of phase between themselves by approximately 120 °, and usually keep the same order of magnitude. Thus, the vector sum tends to a much smaller value much than each one of the leakage currents taken individually, as illustrated in Figure 2.(a) for one given initial capacitance and tangent delta condition.

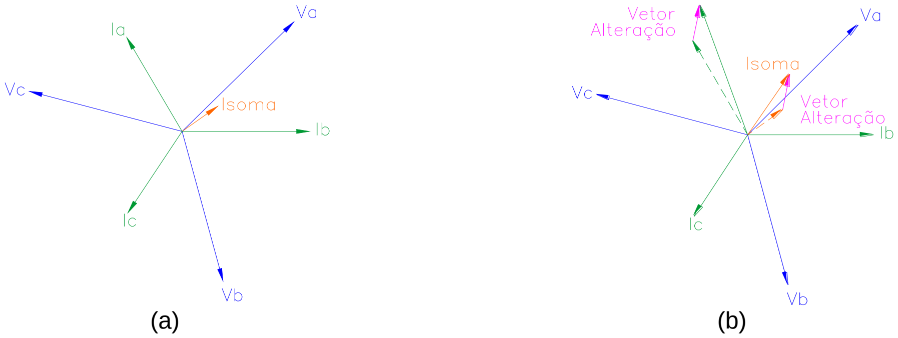

Fig. 2 - Leakage currents of three bushings in a three phase system and their sum, (a) For a given initial conditions; b) With alteration in capacitance and dissipation factor of the phase A bushing.

Assuming now a change in capacitance and in the dissipation factor of the phase A bushing, as shown in Figure 2.(b), the Alteration Vector which expresses the displacement of the current Ia of its initial value until the last value is also reflected in the sum current, which is changed in relation to its initial value according to the same Alteration Vector.

This Alteration Vector has an almost insignificant weight when compared to the magnitude of the phase A leakage current, but this does not take place when this vector is compared to the sum current, which allows its detection and, therefore, the detection of the alteration occurring in the impedance of the bushing under analysis. Thus, the leakage current vector sum technique provides increased sensitivity which makes it possible to monitor changes both in capacitance and in the insulation tangent delta.

However, the leakage currents of the bushings are a function not only of their capacitances and tangent deltas, but also of the system's phase-to-ground voltage. Since the latter are often not available for measurement by the monitoring system, as explained above, the possible influence of variations in the phase-to-earth voltages on the measurements of variations in capacitance and tangent delta is eliminated by advanced proprietary signal processing techniques, which also include statistical data processing.

These statistical procedures imply the use of a data mass, accumulated along system operation time, which is continually updated with the measurements of the most recent leakage currents and sum current. For this reason, the online monitoring system has a response time to variations in capacitance and tangent delta which can vary from several hours to several days, in order to confirm that the change in capacitance and / or Tangent Delta is real and not caused by voltage fluctuations in the electrical system.

Electric industry experts have defended the premise that the evolution of defects in condensive bushings is slow, taking place in days, sometimes weeks, as indicated by Sokolov et. al. [5], which was one of the creators, in the former USSR, of the current leakage sum method monitoring, and as also indicated by Lachman [6]. Gill also says [7]: "These failures occur slowly over time, with one layer slowly failing and burning through the Kraft paper".

Given this premise, the monitoring system's response time to variations in capacitance and Tangent Delta would not present any problem for the detection of defects developing in the bushings, also allowing enough time for the user to take action in case a defect in evolution is detected.

In fact, this premise has proven true in several cases as exemplified by the experience Furnas went through with offline bushing measurements [4], in which a three-month interval between measurements was enough for the detection of several defects slowly evolving in the bushings; and by the experience with online monitoring [2], also in Furnas, which we will describe next.

3.0 - EXPERIENCE WITH ONLINE DETECTION OF SLOW EVOLUTION DEFECT

In November 2005 the BM Treetech (bushing monitoring) system was installed to allow online monitoring of 550 kV and 245 kV bushings in a single-phase 133.33 MVA autotransformer bank; and also to allow monitoring of 550 kV bushings of a 55 MVA single-phase reactor bank. The typical behavior of the capacitance measurements is shown in Figure 3, where there are fluctuations of less than 0.2% in the measurement in the 550 kV autotransformer bushings during the month of January 2007, over one year after installation of the system [2].

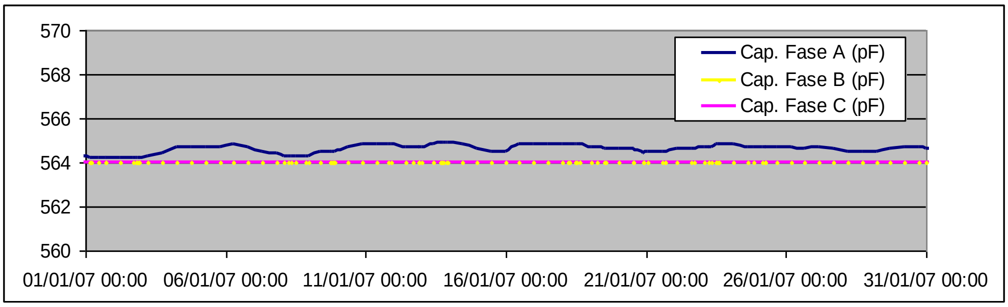

Fig. 3 - Typical behavior of the capacitance measurements in the 550kV autotransformer bushings 550 kV [2]

The installation of the online bushing monitoring system was prompted by suspicions against a certain bushing family. These suspicions were confirmed during the operation of the monitoring system, which in early April 2006 issued an alarm due to a large increase in the capacitance of the 550 kV bushing of the autotransformer phase A, going from 560 pF to 594 pF, an increase of about 6%, as shown in Figure 4 [2].

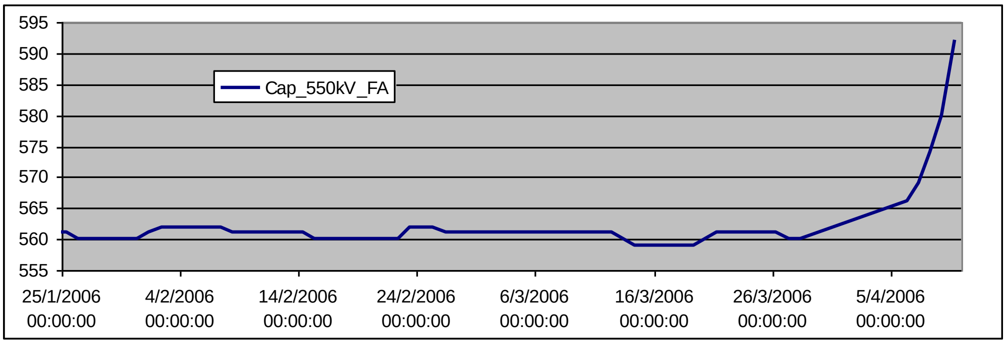

Fig. 4 - Increase in the capacitance in the 550kV bushing of the phase A autotransformer [2]

The evolution of the defect was observed over approximately 10 days, when it was decided that the autotransformer bank should be shut down due to the higher capacitance increase rate [2].

After the bank was de-energized, offline capacitance measurements were taken, in addition to collecting oil samples for dissolved gas analysis in a laboratory. The samples were sent to the Furnas laboratory and also to the autotransformer manufacturer, both indicating similar results, shown in Table 1. High concentrations of combustible gases, mainly acetylene (C_2H_2) with nearly 7000ppm, which confirms the existence of an internal defect evolving in bushing [2].

Table 1 - Gases dissolved in the phase A autotransformer bushing oil [2]

Gas	**H_2**	**O_2**	**N_2**	**CH_4**	**CO**	**CO_2**	**C_2H_4**	**C_2H_6**	**C_2H_2**	**TGC**
Concentration (ppm)	7401	2100	47969	5477	2000	10665	4597	1728	6904	28107

The experience described here is a typical example of a slowly evolving defect in a bushing, as per the premise advocated by Sokolov et. al. [5], Lachman [6] and Gill [7] showing that, in fact, this behavior is possible and occurs in many cases of defects, if not most of them, as Furnas experience with offline measurements in bushings seems to indicate [4], in which three month measurement intervals were short enough to allow detection of various defects developing in bushings.

4.0 - EXPERIMENTS WITH RAPIDLY EVOLVING BUSHING DEFECTS

4.1 Eletrosul Experiment

In October 2008, the BM Treetech bushing monitor was installed in the Santo Ângelo substation in the TF3 transformer bank, which was connected to the Sigma4Net monitoring software. This software stores the measurements in a databank every 15 minutes.

As shown in Figure 5. (a), when the bushing was energized its constructive arrangement originated a predominantly capacitive leakage current, which circulated towards the tap and the measurement entrance of the bushing monitor, and then drained down to the ground.

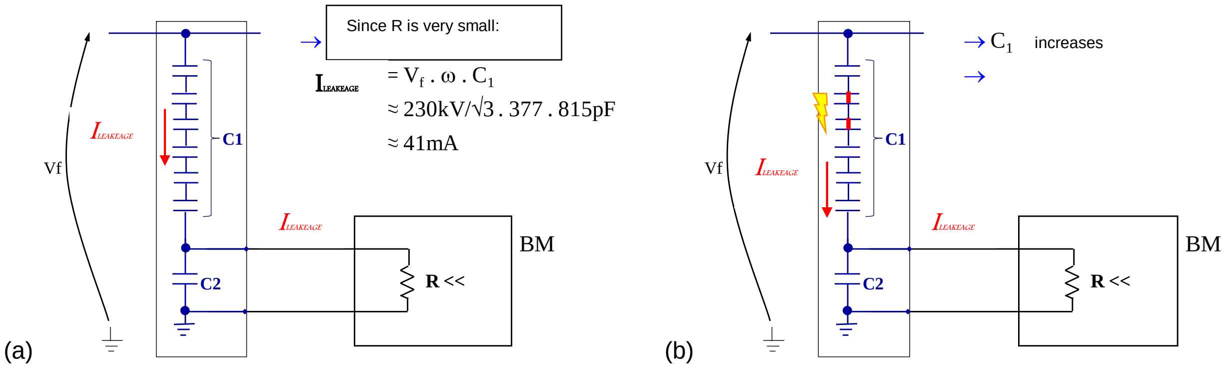

Fig. 5 - Capacitive leakage current with energized bushing. (A) with the bushing in normal conditions, (b) with short-circuited insulation layers.

The leakage current module is determined by the phase-to-ground voltage of the system, by its angular frequency and by the C1 capacitance of the bushing. As shown in Figure 5. (a), for the particular conditions of the 230kV bushings of the TF3 this leakage current would be of around 41mA. In fact, during the two months when the monitoring system was acquiring data, the 230kV bushing leakage currents of phases A, B and C always oscillated around this value (Figure 6), with these three currents always agreeing between them (the observed variations are due to fluctuations in the phase-to-ground voltages of the system). This indicates that, during this period, the C1 capacitances of the bushings were close to their nominal value, that is, there were no short-circuited parts of the main insulation.

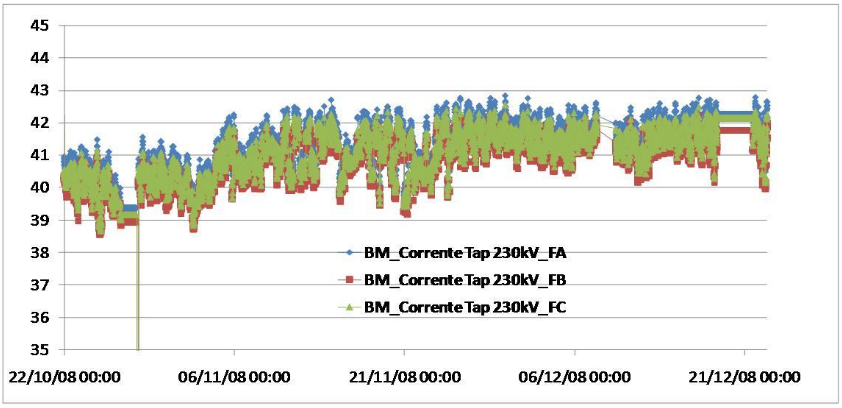

Fig. 6 - Two-month history of the leakage currents of the 230kV TF3 bushings.

Figure 5. (B) illustrates the situation in which the bushing has its main insulation deteriorated and partially short-circuited. In this case, the number of serial capacitors decreases, increasing the C1 equivalent capacitance and consequently the bushing leakage current.

Indeed, Figure 7 shows that at the time the data was recorded into the database at 10:05 pm on Dec. 23, all leakage currents had normal values around the theoretical 41 mA. In the next recording, 15 minutes later (10:20 pm), phase B current had increased around 40%, exceeding 57 mA. As the leakage current is directly proportional to C1 capacitance C1, this indicates the occurrence of a 40% increase in this capacitance, which means that 40% of the insulation would be short-circuited.

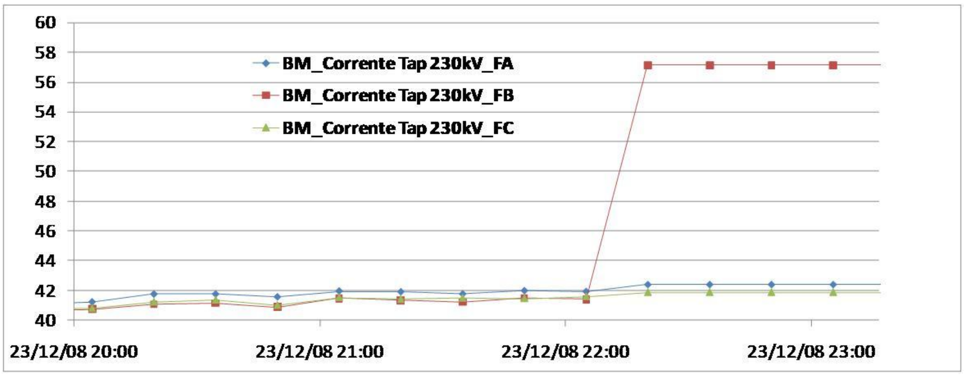

Fig. 7 - Leakage currents of the 230 kV bushings moments before the failure in phase B

It is known from the protection system data that bushing failure and forced shutdown of the TF3 bank took place at 10:12pm, which indicates that the evolution of the bushing defect, from the normal condition until its complete failure, occurred in 7 minutes or less (between 22:05 pm and 10:12 pm).

Later, when the transformer was inspected internally, signs were found that the lower end of the bushing had exploded. The connection between the bushing monitor to the bushing tap was also inspected. It is accomplished through a tap adapter, but there were no signs of connection failure.

4.2 Chesf Experiment

The BM Treetech bushing monitor was installed in Dec. 14, 2005 at Chesf's Xingó Plant, to monitor the 500kV 01T3 step up transformer bank bushings online. Dec 12, 2005 was the day on which the phase B bushing failed [8].

In this case a behavior similar to the one at Eletrosul's Santo Ângelo substation took place, but with a longer defect-to-failure evolution time. In this application, the bushing monitor was installed independently, disconnected from the online monitoring software, so that the available data come from the local mass memory of the bushing monitor.

As shown in Figure 8, the evolution of the capacitance of the bushing until failure occurred in a period of approximately 13 hours. The increase in capacitance compared to the initial value until the moment of failure, was 19% (from 549 pF to 654 pF). In the same period, the tangent delta presented a variation of 10 times, from 0.27% to 2.88%.

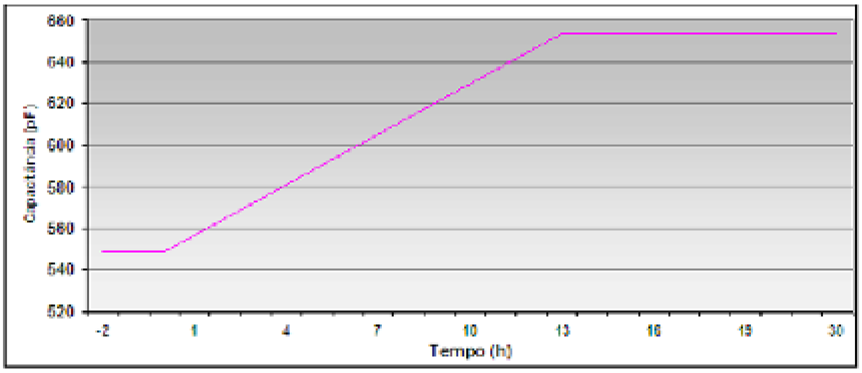

Fig. 8 - Detection of increased capacitance of 525 kV Chesf bushing [8]

Although the duration of the fault is, in this case, much longer than what was recorded in Santo Angelo Substation, it is still shorter to what would be expected based on the common sense of the market [5] [6] [7], which would be weeks or months. Therefore, this experiment helps to confirm the possibility of defects with a much faster evolution then what was initially expected.

The failure of the bushing in Xingó plant occurred when the Bushing BM Monitor had not yet been connected to a remote monitoring system, which is why the defect went unnoticed until the moment of complete failure.

5.0 - ONLINE MONITORING SYSTEM FOR THE DETECTION OF RAPID EVOLUTION DEFECTS

As it has been explained above, several specialists [5] [6] [7] have considered that the evolution of the defects in bushings is slow and gradual, taking weeks or months. In fact, experiments with periodic off-line measurement of capacitance and tangent delta [4], and also with online monitoring [2] support this notion.

However, one should take into account that most data accumulated through bushing maintenance experience originates from periodic offline measurements, with intervals of several years between them [3]. Whereas in most cases offline measurements will only be able to detect defects in evolution and avoid bushing failures in slowly evolving cases, it is natural, therefore, that it would look like all failures evolve slowly. In cases where the bushing failed in the interval between the offline tests it was impossible to know which was in fact the failure evolution speed, and several of them may have evolved quickly.

With the popularization of online monitoring, which started only recently, continuous monitoring of the evolution of changes in capacitance and Tangent Delta have allowed the observation of many cases in which, in fact, the evolution was slow, but others in which the evolution was very rapid or very slow, as shown in the examples of items 4.1 and 4.2 above.

This fact brings up the need for mechanisms in online monitoring systems to detect and send an alarm to the user whenever defects of this kind occur. Simultaneously, one must not lose the ability to detect defects with slow evolution of capacitance and tangent delta, currently available with the technique of vector sum of leakage currents.

To meet this need, the experiments obtained by Treetech in the applications we describe here, in Eletrosul and Chest, as well as other applications which have not been published yet, allowed the development of a system with patents required around the world, for the detection and rapid evolution alarm of defects in which the bushing insulation is short-circuiting (increasing its capacitance) and evolving toward an imminent failure as described below.

5.1 <u>Fault detection with rapid evolution</u>

The immediate effect when bushing insulation is short-circuiting and evolving toward complete failure is an increase in the leakage current, due to the equivalent increase in capacitance when insulation layers are short-circuited.

With that, threshold values are programmed in the bushing monitor for alarm triggering by high and very high leakage current, which provides two levels of alarm with different severity levels. To avoid that alarms are unduly issued as a result of transient overvoltage, alarms have user-adjustable timing.

As shown in section 4.2, the Chesf experience has shown defect evolution lasts several hours. This would be enough time for a decision to be made by the electric power utility's maintenance and/or operations department, once the rapid evolution alarm of a defect is issued by the bushing monitor.

However, Eletrosul's experience (item 4.1) has show a very short evolution time, below 7 minutes, which would virtually leave operators with almost no time for a decision. Thus, one can not exclude the possibility, at the discretion of the user, that the bushing monitor issue a signal to automatically turn off the transformer, even after a short timing after the first alert.

In this case the monitoring system would also act as a protection system, demanding high confidence that the measurement indicative of impending failure is correct. The same need also exists in the case where the shutdown decision is manual and not automatic, because the operator's decision is based on the information provided by the bushing monitor.

To ensure reliability of the measurement and eliminate the possibility of false alarms due to hardware defects, for example, a strict consistency check is performed by the bushing monitor, as described below:

5.2 <u>Alarm consistency check</u>

As shown in Figure 9, any changes in the bushing leakage currents are also reflected by the vector sum of the currents. Therefore, it can be verified whether a high leakage current occurrence is true in one of the phases before high leakage or very high leakage alarms are generated, by comparing the measurements of the individual leakage currents with the vector sum measurement, which must also be consistent.

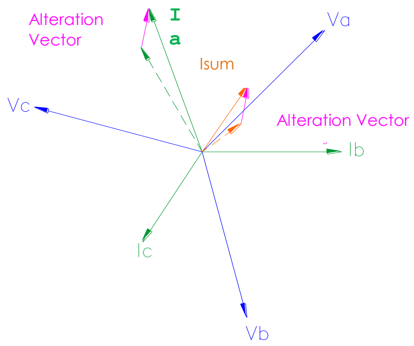

Fig. 9 - Reflection of a change in an individual leakage current (for example, in phase A) on the current vector sum

If a high leakage current measurement is not confirmed when measuring the current sum, the issued alarm is blocked. Instead of the alarm, the bushing monitor issues a self-diagnostic alarm alerting for the existence of an inconsistency of the measurements.

This patent-pending procedure ensures the reliability of the high leakage current alarms, generating in the users the necessary confidence for, based on this information, take actions that may be drastic in many cases, such as the immediate transformer shutdown.

6.0 - CONCLUSIONS

This paper has presented Eletrosul, Chesf and Treetech experiences with the application of bushing online monitoring systems. In these applications, the online monitoring has allowed the detection of defects in the bushings with short evolution times, in the order of hours in one case and minutes in another, thus exposing the existence of failure modes not previously considered by the experts, which in general supposed that failures had long evolution times [5] [6] [7].

The data obtained in these cases demonstrated an important role fulfilled by online monitoring, often unnoticed when these systems are installed, which is to allow the detailed analysis of the defect evolution, which would be impossible without online monitoring, because all evidence would be destroyed after the failure. Thus, monitoring contributes to the increased knowledge of the phenomena associated with failures and consequently to increase the reliability of high voltage equipment and allow improved monitoring of the system itself.

Based on this newly acquired knowledge, it was possible to develop a technique for detection and warning of defects in rapid evolution, equipped with security mechanisms that check the consistency of the information before issuing the alarm. Therefore, measurement reliability increases, making users feel confident about making decisions that may sometimes be drastic, such as shutting down a transformer based on these alarms. Eventually, at the users' discretion, the aforementioned alarms can be used even for automatic shutdown of the transformer since defects with evolution times of a few minutes may not allow time enough for decision making by operators.

It should be noted that the experiences of the electricity sector, both with offline measurements of capacitance and tangent delta [4] and with online monitoring applications [4], indicate that rapid evolution defects have existed in a not negligible number and probably are not the most frequent, the slow evolution defects being predominant. Consequently, the new developed alarm technique must coexist with the already existent techniques, which allow the detection of slow evolution defects in their early stages, and therefore does not eliminate the online capacitance and tangent delta monitoring through the traditional leakage current vector sum, which is valid and recommended to prevent most bushing failures.

7.0 - REFERENCES

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8.0 - BIOGRAPHIC DATA

Marcos E. G. Alves (M' 2007) was born in the city of Rio de Janeiro, State of Rio de Janeiro, Brazil, on July 15, 1975, and has been working for Treetech since 1992. He majored in Power Transformer Control and Monitoring and coordinates the Research, Development and Innovation department. He graduated as an Electric Engineer in 2001 from the Universidade São Judas Tadeu, in São Paulo, and in 2005 he concluded his Masters in the Energy and Automation area from the Universidade de São Paulo. He is currently taking the course of study to obtain his Doctoral degree in Energy from the same university.

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